INVESTIGATION OF OPTIMUM LASER PUMPING

B. N. Srivastava, J. H. Jacob, and M. Rokni
Avco Everett Research Laboratory, Inc.
2385 Revere Beach Parkway
Everett MA 02149

December 1978
Interim Technical Report for Period 16 November 1977 to 15 May 1978

Sponsored by

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
DARPA Order No. 3500 Amend. I

Monitored by

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
Arlington VA 22217

FOREWORD

Contract No.: N00014-75-C-0062

DARPA Order No.: 3500 Amendment 1

Short Title of Work: Investigation of Optimum Laser Pumping

Contractor: Avco Everett Research Laboratory, Inc.
Everett, Massachusetts 02149

Principal Investigator: J.H. Jacob, (617) 389-3000, Ext. 329

Scientific Officer: Director, Physics Program
Physical Sciences Division
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

Effective Date of Contract: 15 August 1974

Contract Expiration Date: 28 February 1979

Amount of Contract: $1,667,957

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* (6) Investigation of Optimum Laser Pumping.		5. TYPE OF REPORT & PERIOD COVERED (9) Interim Technical rept 16 Nov 1977-15 May 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) B.N. Srivastava, J.H. Jacob and M. Rokni		8. CONTRACT OR GRANT NUMBER(s) (15) N00014-75-C-0062 DARPA Order-3500
9. PERFORMING ORGANIZATION NAME AND ADDRESS Avco Everett Research Laboratory, Inc. 2385 Revere Beach Parkway Everett, MA 02149		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 048 450
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency DARPA Order No. 3500 Amendment 1		(11) 12. REPORT DATE December 1978 13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)* Office of Naval Research Department of the Navy Arlington, VA 22217		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

(12) 35 p.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Visible Lasers
UV Lasers
Discharge Physics
Boltzmann Analysis

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An important task of the Optimum Pumping Technology program is the investigation of the feasibility of discharge pumping electronic transition lasers. Such an investigation requires a detailed knowledge of the secondary electron transport properties that may be obtained from a numerical solution of the Boltzmann code. An example of an electronic transition discharge pumped laser is HgCl*.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

048 450

20. Abstract (continued)

A theoretical investigation of the e-beam controled discharge pumping of the mercury halide lasers requires a coupled solution of the electron transport Boltzmann Equation and dominant kinetics rate equations. The general only the lowest order diffusion approximation of the Boltzmann Equation is used for this purpose. This is because the more general Boltzmann Equation is complex in nature. To insure the validity of the P_1 approximation an analysis to determine the error of the lowest order diffusion equation is made. The analysis shows that if the spatial derivative of the distribution function can be neglected, i.e., for a distributed source of electrons, the P_1 approximation is valid for all the cases considered. When the spatial derivative cannot be neglected, which is the case for a spatially localized source of electrons, then the region of validity of the P_1 approximation is much more restrictive. High pressure discharges are examples of a distributed source. Electron beams generated for swarm experiments are examples of a spatially localized source.

In order to address the key technical issue of discharge stability in mercury halide lasers; a theoretical study is made to predict the stability criteria in recombination and attachment-dominated metal vapor discharges. In mercury halide laser discharges, a relatively large excited state population exists which dominates the stability of these discharges. This occurs because the excited states have a smaller ionization potential and larger ionization cross-section than the ground state. As a result, multi-step ionization is the dominant ionization. When three step-ionization is dominant and electron mixing of the excited states is unimportant, attachment-dominated discharges will be stable if the attachment rate $\beta \geq m\ \nu_{i0}$ where $2 < m \leq 3$ and ν_{i0} is the equilibrium ionization rate. For a recombination dominated discharge the criterion in this limit is $\alpha\ n_{e0} \geq m\ \nu_{i0}$ where $1.0 < m \leq 1.5$ and α is the recombination coefficient and n_{e0} is the equilibrium electron density.

TABLE OF CONTENTS

I. INTRODUCTION

In the last three years ARPA/ONR sponsored Visible/UV laser programs of AERL have led to the discovery and successful devlopment of important rare gas halide lasers. Specifically, we have obtained 12 J/liter with a 10% intrinsic efficiency from KrF* by pure e-beam pumping and 10 J/liter with a 9.5% intrinsic efficiency from e-beam controlled discharge pumping. In the last year another class of visible lasers, the mercury halides, have been discovered.[1,2] These molecules, like the rare gas halides, have ionic upper levels. Hence, the formation kinetics of the upper laser level should be rapid and efficient due to the long range attractive forces involved in ion-ion interactions. Since the ionization energy of mercury is lower than that of the rare gases, the mercury halides radiate at a longer wavelength than the rare gas halides. To date, lasing action has been obtained in HgCl at 5576 Å and HgBr at 5018 Å.

E-beam controlled discharge pumping of the mercury halide lasers could lead to very high overall laser system efficiencies-efficiencies as high as 20%. In order to achieve these high efficiencies, efficient production of mercury 3_p manifold, Hg* (^{3}P), in a stable discharge run at high enhancement ratios (discharge power/e-beam power) must be demonstrated. The key technical issues are:

1) Hg (^3P) production efficiency

2) Discharge stability

3) Discharge enhancement ratio

In order to theoretically predict the characteristics of the mercury halide lasers a coupled solution of the electron transport equation and kinetic rate equations that model the key formation and quenching kinetics is required. Such a solution is necessary because the electron impact excitation and ionizatoin rates are dependent on the discharge power deposited in the gas. The solution of the Boltzmann Equation for this purpose is generally obtained by considering only the lowest order diffusion or P_1 approximation. This is because the more general form of the Boltzmann Equation is not amenable to analytic solutions. The P_1 approximation of the Boltzmann Equation has proved most useful in the understanding of high pressure discharges. However such an approximation is not necessarily valid for all cases under consideration. Hence, the first part of this report investigates the regions of validity of the P_1 approximation.

One of the major technical issues of the e-beam controlled discharge pumping of the mercury halide lasers is the discharge stability. The mercury halide laser discharges which are typical of attachment-dominated discharges are characterized by a relatively large excited state population. These excited states dominate the stability of these discharges. Typically they have a smaller ionization potential and a larger ionization cross

section than the ground state. As a consequence these effects lead to a condition where multi-step ionization dominates. A theoretical study to establish the stability criteria (for both attachment and recombination dominated discharges) is reported in the second part of this report.

II. ON THE DIFFUSION APPROXIMATION OF THE BOLTZMANN EQUATION FOR SLOW ELECTRONS

The lowest order diffusion or P_1 approximation of the Boltzmann equation has proved most useful in the understanding of high pressure discharges. There have been several efforts addressing the domain of applicability of this approximation.[1] In one of the earliest discussion Holstein[2] has shown that the diffusion approximation is valid when the elastic cross section for electron heavy particle collisions is large compared to the inelastic cross section. This criterion has also been used in the Bethe Age theory for electron and neutron diffusion.[3,4] While, for most gases, this criterion is well satisfied, there are instances when the magnitude of inelastic and elastic cross sections are comparable. For example, recent measurements[5] of the vibrational cross section of N_2 evaluates the peak cross section in the energy range of 2-3 eV, to about 12 $\mathring{A}$, which is comparable to the peak elastic cross section of 30 $\mathring{A}^2$ for N_2 evaluated by Englehardt, Phelps and Risk.[6]

In this article we investigate the applicability of the P_1 approximation by considering a narrow band of electrons in energy space. It is shown that the angular distribution function depends on two dimensionless parameters, γ and ξ. γ is the ratio of the energy gained by an electron in the electric field per transport mean free path to the electron energy and ξ is the ratio of the

energy lost by inelastic collisions per transport mean free path along its trajectory to the electron energy. The former is a familiar parameter in plasma physics, while the later is proportional to the ratio of the inelastic to the elastic cross sections. The analysis presented suggests that when the spatial derivative of the distribtuion function cannot be neglected, the P_1 approximation is not valid for values of γ and ξ that approach unity. However, when the spatial derivative can be neglected, the error in P_1 approximation is limited to 5% for all electron energies and for all values of γ and ξ considered. These results imply that the applicability of the P_1 approximation depends strongly on whether the sources of electrons are spatially localized or uniformly distributed throughout the volume under consideration. This is because for the localized source, the spatial variation of the electron density is important, while for a uniformly distributed source the spatial variation may be neglected. Spatially localized sources of electrons that diffuse between two electrodes are used in swarm experiments.[7] Hence, for gases like N_2, for which values of γ and ξ are large, the evaluation of impact parameters from swarm data using the P_1 appoximation will be suspect. In a high pressure discharge, however, secondary electrons are created uniformly (at least on the scale length of the transport mean free path) through the discharge volume. For such cases, therefore, the spatial derivative of the distribution function may be neglected.

The transport of a broad area electron source in the presence of collisions can be described by the one dimensional Boltzmann equation,[8]

$$2\mu\ \lambda\ \frac{\partial f}{\partial x} + 2\ eE\ \lambda\ \mu\ \frac{\partial f}{\partial w} + \gamma\ (1-\mu^2)\ \frac{\partial f}{\partial \mu} = 2\lambda\left\{\left.\frac{\partial f}{\partial s}\right|_i + \left.\frac{\partial f}{\partial s}\right|_e\right\} \qquad (1)$$

where the distribution function f is a function of the kinetic energy w, angular coordinate μ and spatial coordinate x. μ is the cosine of the angle between electron trajectory and $\bar{E}$, which is assumed to be along the x direction. The transport mean free path λ is defined in the usual manner. The parameter γ is the ratio of the energy gained per transport mean free path to the electron energy, i.e.,

$$\gamma = \frac{eE\lambda}{w} \qquad (2)$$

For isotropic elastic scattering, $\left.\frac{\partial f}{\partial s}\right|_e$ is given by[8]

$$2\lambda\ \left.\frac{\partial f}{\partial s}\right|_e = -2f + \int_{-1}^{+1} f\ (\mu')\ d\mu \qquad (3)$$

We will assume that an inelastic scattering process changes only the energy of the electron. Then for the J^{th} excitation process

$$\left.\frac{\partial f}{\partial s}\right|_i = \sum_J \left\{P_J\ (w + E_J)\ f\ (w + E_J) - P_J\ (w)\ f\ (w)\right\} \qquad (4)$$

where $P_J(w)$ is the average number of collisions per unit distance along the electron trajectory. E_J is the energy lost after the collision. $P_J(w)$ is zero for $w < E_J$.

The usual method of solving the Boltzmann equation for high pressure discharges is to neglect the variations of f with x and then expand f as a sum of Legendre polynomials. Because of the complexity only the first two polynomials are generally retained. This procedure is valid provided, of course, that f is nearly isotropic. A method for checking the validity of such an approach is to simplify Eq. (1) by considering a narrow beam of electrons (of width Δw) in energy space having a mean energy w_0. Integrating Eq. (1) over all energy, we obtain

$$2\mu\lambda_0 \frac{\partial F}{\partial x} + 2\xi_0 F - 2\gamma_0 \mu F + \gamma_0 (1 - \mu^2) \frac{\partial F}{\partial \mu} = - 2F + \int_{-1}^{+1} F(\mu)\, d\mu \tag{5}$$

where

$$F = \int_0^\infty dw\ w\ f(w) \tag{6}$$

The dimensionless parameter ξ is the ratio of energy lost by the electrons per transport mean free path to the energy of the electron[8]

$$\xi_0 = \frac{\chi_0 \lambda_0}{w_0} \text{ when } E_J \sim \Delta w << w_0 \tag{7}$$

$$\xi_0 = \frac{\chi_0 \lambda_0}{E_J} \text{ when } E_J \lesssim w_0 \tag{8}$$

The two definitions of ξ_0 are obtained from Eq. (6) for the two limiting conditions. Equation (7) is obtained by a Taylor expansion of the first term on RHS of Eq. (4), while for a narrow beam

this term will have a negligible contribution when $E_J \approx w$. χ_0 is the energy lost by the electron per unit path length along its trajectory and is given as

$$\chi_0 = \sum_J E_J P_J = N \sum_J Q_J E_J \tag{9}$$

where Q_J is the inelastic cross section for the J^{th} process and N is the number density of scatterers. From Eqs. (7), (8) and (9), it is clear that ξ_0 is proportional to the ratio of the inelastic cross section to the elastic cross section. In fact, when $E_J \approx w_0$, which is near or just above the threshold of the excitation process, ξ_0 is precisely the ratio of the inelastic cross section to the elastic cross section. Note that ξ_0 evaluated by Eq. (7) is always less than when evaluated by Eq. (8), except when $w_0 = E_J$. As the two values are similar and we are only making estimates of the error, we will use Eq. (7) in the subsequent discussion. ξ_0, γ_0, and χ_0 are all evaluated at the particular energy w_0.

Dropping the subscript 0 and integrating Eq. (5) over all μ we get

$$\lambda \frac{dJ}{dx} + \frac{\xi J}{\langle \mu \rangle} = 0 \tag{10}$$

where J is the electron current density and

$$\langle \mu \rangle = \int_{-1}^{+1} F \mu d\mu \left\{ \int_{-1}^{+1} F d\mu \right\}^{-1}$$

or

$$J = J_0 \exp - \left(\int^{x} dx' \frac{\xi}{\langle\mu\rangle} \frac{1}{\lambda}\right) \tag{11}$$

Assuming

$$F \sim g(\mu) \exp \left(- \int^{x} dx' \frac{\xi}{\langle\mu\rangle} \frac{1}{\lambda}\right) \tag{12}$$

Eq. (5) reduces to

$$\frac{-2\mu g}{\langle\mu\rangle} + 2\xi\, g - 2\gamma\, \mu g + \gamma\, (1 - \mu^2) \frac{dg}{d\mu} = - 2g + \int_{-1}^{+1} g(\mu')\, d\mu' \tag{13}$$

Making a Legendre polynomial expansion of $g(\mu)$

$$g(\mu) = \sum_{\ell} A_\ell P_\ell(\mu) \tag{14}$$

Equation (13) can be represented by an infinite set of simultaneous equations

$$A_{n+1} \left(\frac{n+1}{2n+3}\right) \left(\gamma n - \frac{2\xi}{\langle\mu\rangle}\right) + A_n \left[2(1-\delta_{0,n}) + 2\xi\right]$$

$$- A_{n-1} \left(\frac{n}{2n-1}\right) \left[\frac{2\xi}{\langle\mu\rangle} + (n+1)\, \gamma\right] = 0 \tag{15}$$

Using Eq. (15) we may solve for the coefficients A_ℓ by truncating the series at some arbitarary $\ell = L$. An iterative procedure is necessary as $\langle\mu\rangle$ is not known a priori. In this manner one may obtain a solution of $g(\mu)$ to any desired accuracy. Note that when the variation of f with x is neglected then this equation takes a simpler form ($n > 0$)

$$A_{n+1}\left(\frac{n+1}{2n+3}\right)\gamma n + An\,(2+2\xi) - A_{n-1}\left(\frac{n}{2n-1}\right)(n+1)\,\gamma = 0 \qquad (16)$$

for which an iterative procedure is not necessary. The error in the P_1 approximation may be evaluated by the following ratio

$$\sum_{n=2} An^2 \Big/ \sum_{n=0} An^2 \qquad (17)$$

It is interesting to note that the series represented by Eq. (16) converges much more rapidly than Eq. (15) for a given γ and ξ, signifying that when the spatial derivative is neglected the distribution function is much more isotropic. The error for the case when electron distribution is not a function of x, is $\leq$ 5% for all γ and ξ values considered in Figure 1. However, the same argument does not apply to the situation when the variation of f with x cannot be neglected, as in the case of electron swarm experiments. This result is supported through Figure 1 that shows the contours of the error as a function of γ and ξ. As one expects, the error increases as both γ and ξ increase. Figure 2 shows the distribution function obtained from our Boltzmann code along with our estimate of error and the parameters γ and ξ for an electric field of 1 kV/cm amagat in nitrogen. The error < 1% for most of the electrons having an energy > 0.2 eV. The error is large for a few electrons near zero energy as Holstein[2] has pointed out. This is because γ is large in this region. Since relatively large numbers of electrons have energies beyond 0.2 eV for this electric field (as is observed from the distribution

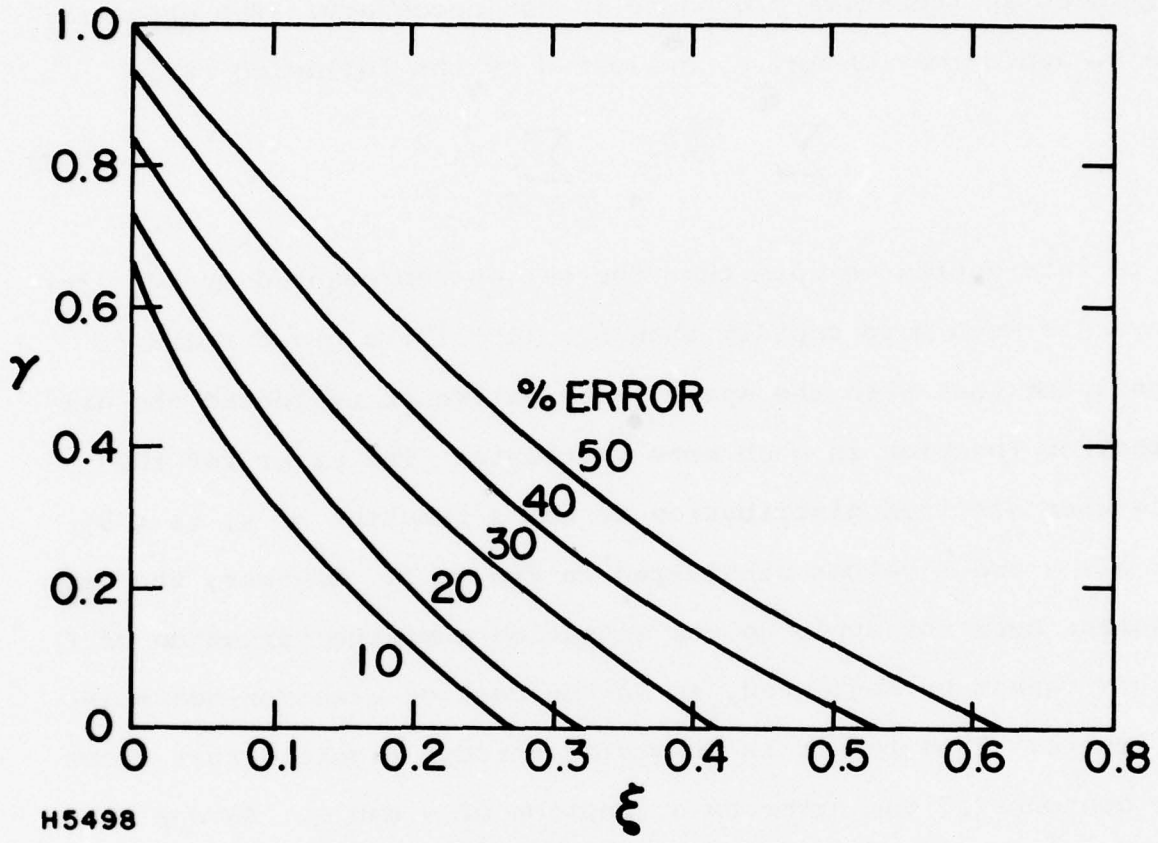

Figure 1 % Error in Using P_1 Approximation for Various Values of Parameters γ and ξ

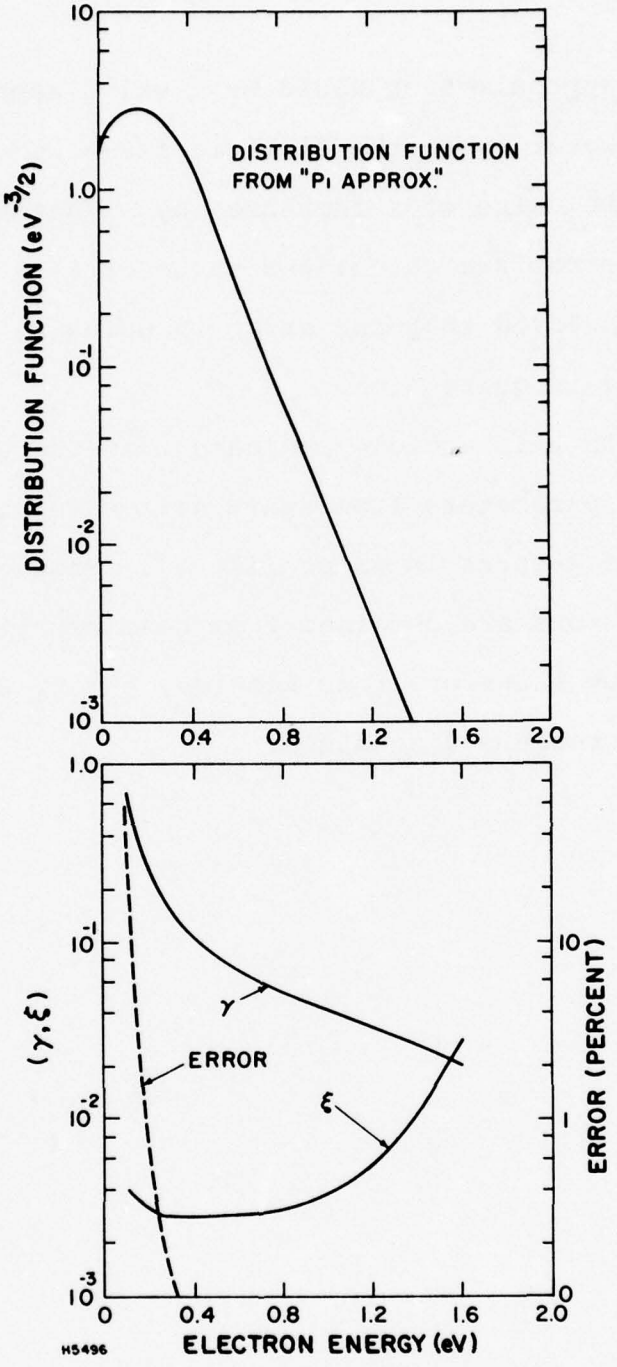

Figure 2 % Error in Using P_1 Approximation for Nitrogen at 1 kV/cm Amagat at Various Electron Energies

function), the P_1 approximation would be a valid approximation for this case. However, when the electric field is increased to 20 kV/cm amagat, the value of γ increases by a factor of 20 and the corresponding error and calculated value of ξ is shown in Figure 3. It is observed that the error in using P_1 approximations for this case is quite high.

The results in this article indicate that the evaluation of electron impact parameters from swarm data using the P_1 approximation will be suspect in gases like N_2. However, if the detailed cross sections are obtained from beam experiments, these include the momentum transfer cross section, the P_1 approximation is valid for high pressure discharges.

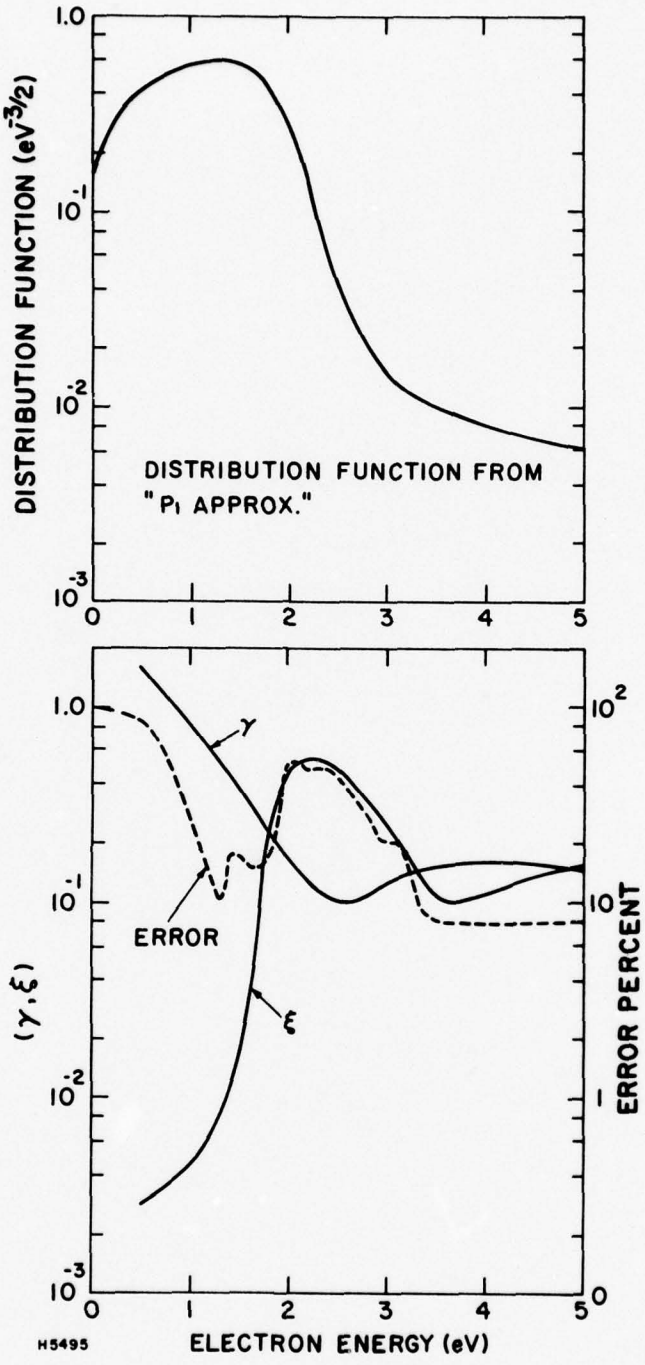

Figure 3 % Error in Using P_1 Approximation for nitrogen at 20 kV/cm Amagat at Various Electron Energies

III. STABILITY CRITERIA IN METAL VAPOR DISCHARGES

The stability criterion for discharges where excited state (two-step) ionization plays an important role has been previously investigated.[9] Such a stability criterion has been shown[10] to describe high power rare gas halide laser discharges when the discharge electric field is held constant during the discharge pulse. In this letter, the stability of metal vapor discharges is investigated. Interest in metal vapor lasers has been heightened since the observation of lasing action in HgCl* at 5576 Å by both pure e-beam pumping[11] and e-beam controlled discharge pumping.[12] In the high power metal vapor discharges, there exists a relatively large excited state population[13] which dominates the stability of these discharges. This occurs because typically the excited states have a smaller ionization potential and a larger ionization cross section than the ground state. For high power discharges such as those used in pumping electronic transition lasers, these effects lead to a condition where multi-step ionization dominates. Both attachment and recombination metal vapor discharges have been considered in this paper. The mercury halide lasers are examples of attachment dominated metal vapor discharges. The CdHg* laser[14] is typical of recombination dominated metal vapor discharges. In the subsequent discussion on discharge stability, conditions typical of those found in these lasers will be considered as examples of the stability criteria derived.

Figure 4 shows the energy levels of cadmium, mercury and argon (used as a buffer gas). In cadmium for example, it requires 3.7 eV to create Cd* and another 5.3 eV to ionize Cd* whereas it requires only 2.6 eV to produce Cd** from Cd* or to ionize Cd**. As indicated in Figure 4, Cd* and Cd** are a number of relatively closely spaced levels. As the electron temperature will typically be larger than this spacing, we assume that the manifold of states represented by Cd* and Cd** will be completely mixed and hence can be represented by a single level. Since the average electron energy in these discharges is 1-1.5 eV three-step ionization tends to dominate at the electron densities of interest. However, if the electron density is large such that the mixing of the two excited states (Cd* and Cd**) by collisions of the first and second kind is far more rapid than excited state reactions with other heavy particles or ionization then the Cd* and Cd** may be treated as a single level and the two-step ionization criterion[9] derived previously is valid. In the cadmium mercury system, stabilization of the discharge current will be achieved through loss of secondary electrons by recombination. In the case of the HgCl* laser, the excited states Hg* and Hg** will play a dominant role in discharge stability and discharge stabilization will be achieved through loss of electrons by attachment.

Three equations are important in determining the stability of the discharge in the presence of rapid excited state ionization. The first describes the production and loss of discharge electrons.

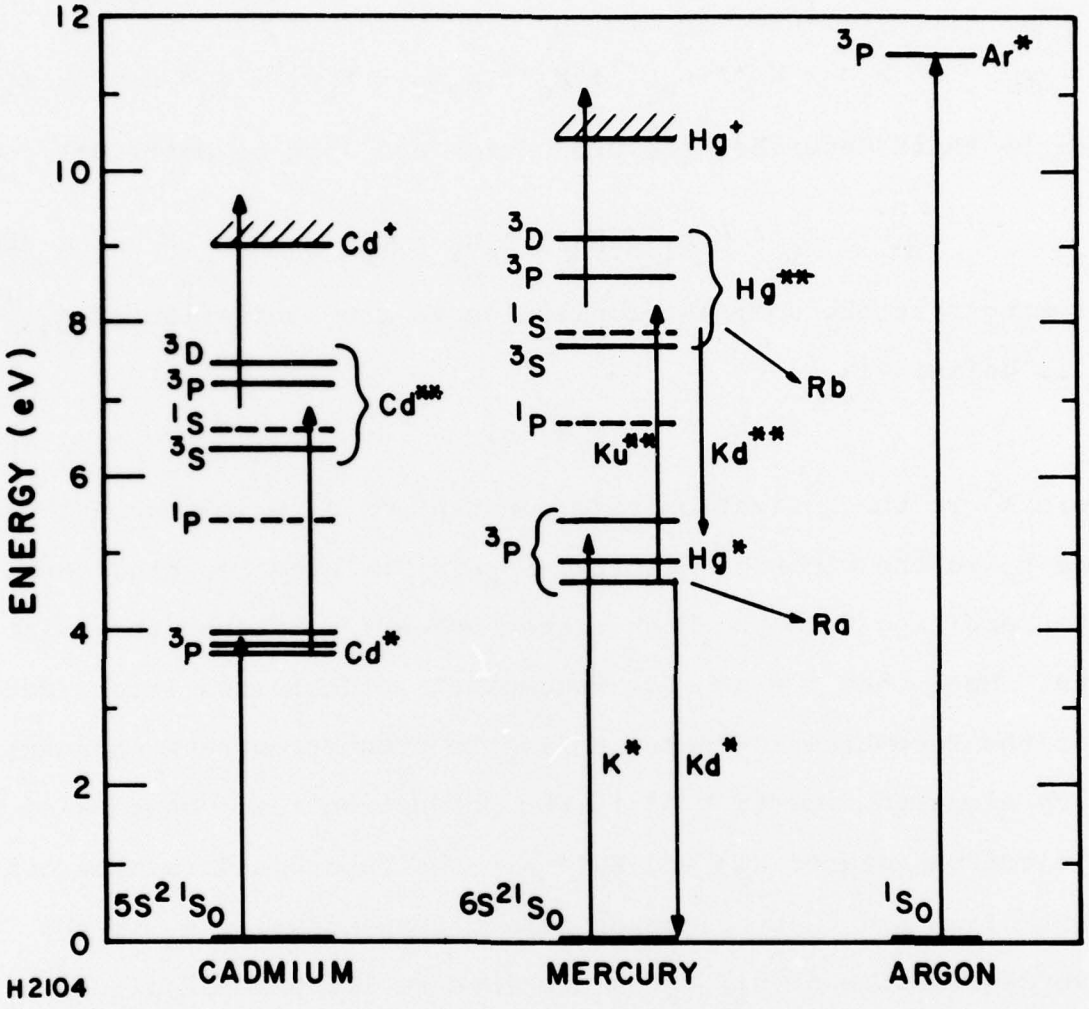

Figure 4 Energy Levels for Cadmium, Mercury and Argon

$$\frac{dn_e}{dt} = S_{eb} + (\nu_i - \beta)n_e \tag{18}$$

while the second describes the production and loss of Hg*(Cd*),

$$\frac{dn_1}{dt} = K^* n_e n - K_u^{**} n_e n_1 + K_d^{**} n_e n_2 - R_a n_1 - K_d^* n_1 n_e \tag{19}$$

and the third describes the production and loss of Hg**(Cd**),

$$\frac{dn_2}{dt} = K_u^{**} n_e n_1 - K_d^{**} n_e n_2 - R_b n_2 - \nu_i n_e \tag{20}$$

Assuming that the dominant ionization is the ionization of n_2,[15] ν_i is defined as

$$\nu_i = K^+ n_2 \tag{21}$$

where K^+ is the ionization rate constant of n_2 by electron impact. Here n_e is the electron density; S_{eb} is the electron production rate resulting from the high energy e-beam; β is the attachment rate. Note that $\beta = \alpha n_e$ for recombination dominated laser (CdHg*); α is the recombination rate; K* is the production rate constant of n_1 by electron impact; K_u^{**} is the production rate constant of n_2 by electron impact; K_d^* and K_d^{**} are the superelastics rate constant of n_1 and n_2 by electron impact respectively; R_a is the inverse lifetime of n_1; R_b is the inverse lifetime of n_2; n, n_1 and n_2 represent the number densities Hg(Cd), Hg*(Cd*) and Hg**(Cd**) respectively. Figure 4 depicts schematically the terminology of the rates described above. In the present analysis we will assume that the ground state density n is constant. Further, only transitions between adjacent levels have been considered as these rate constants will be by far the most rapid.

Equations (18) to (20) are three nonlinear simultaneous differential equations. If the discharge electric field is a constant in time, we can linearize by letting,

$$n_e = n_{e_0} + n_e(t),\ n_1 = n_{1_0} + n_1(t),\ n_2 = n_{2_0} + n_2(t) \qquad (22)$$

The equilibrium conditions, n_{e_0}, n_{1_0} and n_{2_0} is readily obtained from Eqs. (18) to (20). The normalized perturbed Eqs. (18) to (20) are given by,

$$\frac{d\bar{n}_e}{dt} = -C_1\bar{n}_e + C_2\bar{n}_2 \qquad (23)$$

$$\frac{d\bar{n}_1}{dt} = R_a\bar{n}_e + C_3\bar{n}_2 - C_4\bar{n}_1 \qquad (24)$$

$$\frac{d\bar{n}_2}{dt} = R_b\bar{n}_e + C_5\bar{n}_1 - C_5\bar{n}_2 \qquad (25)$$

where $\bar{n}_e = n_e/n_{e_0}$, $\bar{n}_1 = n_1/n_{1_0}$, $\bar{n}_2 = n_2/n_{2_0}$

and

$$C_1 = \frac{\alpha n_{e_0}^{\ 2} + S_{eb}}{n_{e_0}} \quad \text{Recombination dominated} \qquad (26a)$$

$$= \frac{S_{eb}}{n_{e_0}} \quad \text{Attachment dominated} \qquad (26b)$$

$$C_2 + K^+ n_{2_0},\ C_3 = \frac{K_d^{**} n_{e_0} n_{2_0}}{n_{1_0}},\ C_4 = R_a + K_u^{**} n_{e_0},\ C_5 = K_d^{**} n_{e_0} + R_b \qquad (27a\text{-}d)$$

Equations (23), (24) and (25) can be combined by elimination to yield

$$\frac{d^3 \bar{n}_e}{dt^3} + A \frac{d^2 \bar{n}_e}{dt^2} + B \frac{d\bar{n}_e}{dt} + C\bar{n}_e = 0 \qquad (28)$$

where A, B and C are functions of C_1, C_2, C_3, C_4 and C_5. For Eq. (28) to be of stable type (i.e., the characteristic equation has real negative roots or the real part of the complex roots be negative) the following conditions[16] must be satisfied,

$$A > 0,\ B > 0,\ C > 0,\ AB-C > 0 \qquad (29a\text{-}d)$$

We have analyzed Eq. (29a-d) in order to establish stability criteria for recombination and attachment dominated discharges. The most restrictive condition is obtained from Eq. (29c) (i.e., $C > 0$) and is given as,

$$\alpha n_{e_0} \geq (1 + \varepsilon/2)\ \nu_{i_0} \quad \text{Recombination dominated} \qquad (30a)$$

$$\beta \geq (2 + \varepsilon)\ \nu_{i_0} \quad \text{Attachment dominated} \qquad (30b)$$

where $\nu_{i_0} = K^+ n_{2_0}$, $\varepsilon = \dfrac{A\delta_1\delta_2 - 1}{1+A(\delta_1+\delta_2)+A\delta_1\delta_2}$, $\delta_1 = \dfrac{R_a}{(K_u^{**} + K_d^*)n_{e_0}}$

$$\delta_2 = \frac{R_b}{(K_d^{**} + K^+)n_{e_0}}$$

and $A = (K_d^{**} + k_d^+)(K_u^{**} + K_d^*)/(K^+K_u^{**} + K_d^*K^+ + K_d^{**}K_d^*)$

It can be shown that Eq. (30) is sufficient to ensure the validity of Eq. (29a-d). In such cases Eq. (28) would predict temporally decaying solutions indicating stable discharges. The parameter δ_1 and δ_2 are the ratios of characteristic time for loss of electrons by electron impact to that due to heavy particle collisions for the two excited states. It is observed that when δ_2 or δ_1

approaches zero (with $A\delta_1$ or $A\delta_2 \gg 1$), two-step ionization limit similar[17] to that derived by Daugherty, Mangano and Jacob[9] is recovered. This corresponds to a situation when n_1 and n_2 are completely mixed by electrons. When δ_1 and δ_2 both approach zero, the usual single-step stability criteria ($\beta \geq \nu_{i_0}$, and $\alpha n_{e_0} \geq \nu_{i_0}$) is recovered. For this case the excited state population will come into thermal equilibrium with the secondary electrons.[18] It is noticed from the expression for ε that when electron mixing of the excited states is unimportant (i.e., $\delta_1, \delta_2 > 1$), its value is bounded (note that $A \geq 1$) by $0 < \varepsilon \leq 1$. The stability criteria for three-step dominant ionization, therefore, is given by αn_{e_0} (or β) $\geq m\nu_{i_0}$ where $1 < m \leq 3/2$ for recombination and $2 < m \leq 3$ for attachment dominated discharge. Our numerical calculations for laser discharges typically indicate $\delta_1 \simeq 2$, $\delta_2 \simeq 1.0$ and $A \simeq 1.1$ for CdHg* and $\delta_1 \simeq 13$, $\delta_2 \simeq 1$ and $A \simeq 2$ for HgCl* discharge. These correspond to values of $m = 1.1$ and 2.5, respectively. In general, knowledge of the parameters δ_1, δ_2, A and the equilibrium values, n_{e_0}, ν_{i_0}, etc. (obtained by solving Eqs. (18) to (20), would determine the value of m below which the discharge will go unstable. Note also that when the electron production rate $S_{eb} = 0$, then from Eq. (18) the equilibrium condition for an attachment dominated discharge is $\beta = \nu_{i_0}$, which is in violation of Eq. (30) when $\varepsilon > -1$. Hence, an external source for electron production is essential for discharge stability of an attachment dominated discharge when $\varepsilon > -1$. By a similar reasoning, a

nonzero S_{eb} is essential for the stability of a recombination dominated discharge when $\varepsilon > 0$.

In order to demonstrate the validity of the linearized analysis presented earlier, we have also numerically solved the system of Eqs. (18) to (20). Figure 5 shows the results of such an analysis. Discharge conditions were selected such that $m \simeq 3$ for this case. On the left-hand side we have the stable discharge condition, i.e., one-third of the attachment rate is slightly greater than the equilibrium ionization rate. Note that the discharge current reaches a constant value asymptotically. If we keep everything constant but decrease the attachment rate by 5%, we observe that the ionization rate increases and after about 0.8 μsec becomes greater than one-third of the attachment rate. The discharge current grows and shows stronger than exponential growth after about 0.8 μsec. In Figure 6 we show a similar behavior for recombination dominated discharge. In this case, discharge conditions were selected such that $m \simeq 1.5$. On the left-hand side we have again the stable discharge condition as long as $\alpha n_e \geq 3/2\ \nu_i$ and the discharge current reaches a constant value asymptotically. If the recombination rate is reduced by 10%, we observe that the ionization rate increases and becomes $> 3/2\ \alpha n_e$ at about 0.7 μsec. The discharge current exhibits a stronger than exponential growth after about 0.7 μsec.

The volumetric instability described in this letter predicts a temporal increase of the secondary electron density that is faster than exponential in a spatially uniform manner. For spatial

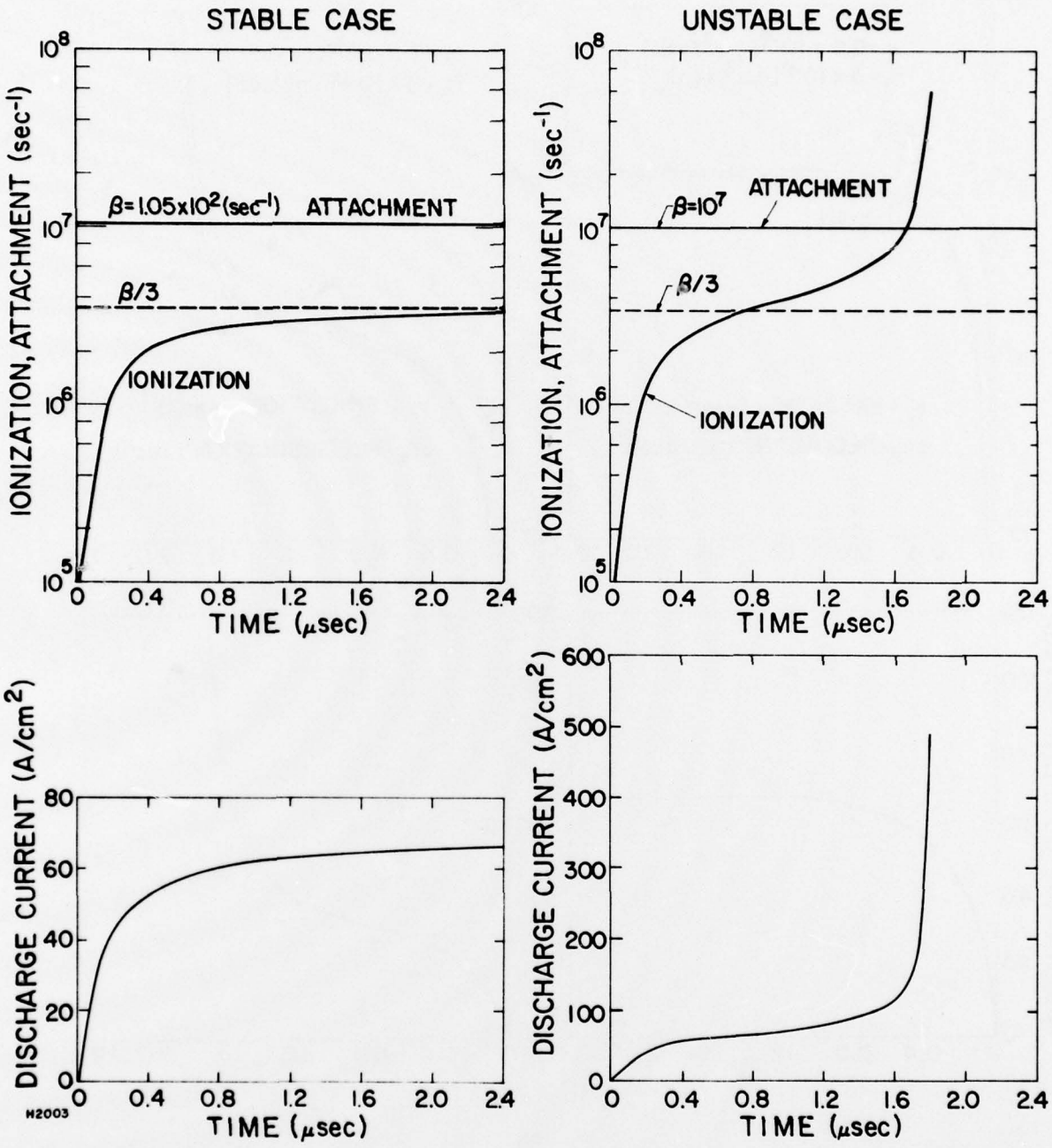

Figure 5 Results of a Numerical Analysis of a System of Eqs. (1)-(3) for Attachment Dominated Discharge

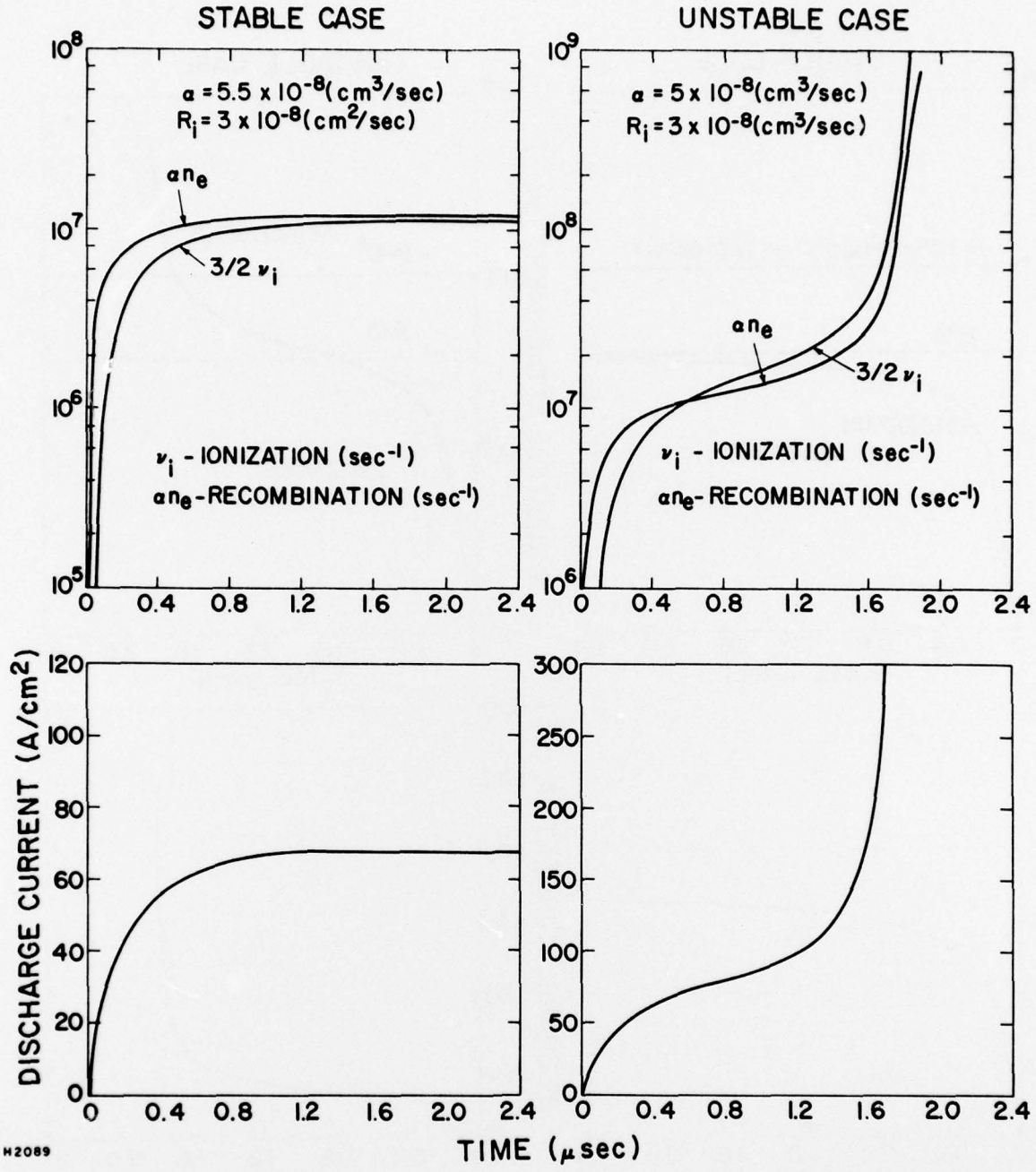

Figure 6 Results of a Numerical Analysis of a System of Eqs. (1)-(3) for Recombination Dominated Discharge

regions in the discharge where the stability criteria derived above are not satisfied, the discharge will go unstable. These locally unstable regions will lead to arc formation if the variation in the power deposition is in the dimension transverse to the electric field. Consequently, for a constant electric field, stability is guaranteed only if the criteria derived above are satisfied at every point in space. In principle, resistive or inductive ballasting can be used to stabilize the discharge. However, the stabilizing influence of the ballast depends on the ratio of the transverse area which is unstable to the total area of the discharge. As this ratio decreases, the effectiveness of resistive or inductive ballasting decreases.

REFERENCES

1. For a comprehensive review of past work see Aldo L. Gillardini, Low Energy Electron Collision in Gases, John Wiley & Sons (1972).

2. Holstein, T., Phys. Rev. 70, 367 (1946).

3. Bethe, H.A., Rose, M.E. and Smith, L.P., Proc. Amer. Phil. Soc. 78, 573 (1938).

4. Davison, B., Neutron Transport Theory, Oxford University Press (1957).

5. Bonness, M.J.W. and Wong, S.F., (private communication).

6. Englehardt, A.C., Phelps, A.V. and Risk, C.G., Phys. Rev. 135, A1566 (1964).

7. For a discussion of swarm experiments see Ref. 1, Chapter 3.

8. Bethe, H.A. and Jacob, J.H., Phys. Rev. A16, 1952 (1977).

9. Daugherty, J.D., Mangano, J.A. and Jacob, J.H., Appl. Phys. Lett., 28, 581 (1976).

10. Jacob, J.H. and Mangano, J.A., Appl. Phys. Lett., 28, 724 (1976).

11. Parks, J.H., Appl. Phys. Lett. 31, 192 (1977).

12. Jacob, J.H., Mangano, J.A., Rokni, M. and Srivastave, B.N., presented at the 20th Gaseous Electronic Conference, Oct. (1977); McCuskey, M., et al., ibid; Watt, N., private communication.

13. Shuker, R., Morgan, W.L., Gallagher, Alan, and Phelps, A.V., presented at the 30th Annual Gaseous Electronic Conference Oct. (1977).

14. McGeoch, M.W., Fournier, C.R. and Ewart, P., J. Phys. B, Atomic and Molecular Physics 9, p. L 121 (1976).

15. The technique presented here can be further extended by including ionization from other levels.

16. Birkoff, G. and MacLane, S., "Modern Algebra," The MacMillan Company, NY. p. 115.

17. It can be shown by including the superelastic and ionization loss terms, which were neglected in Eq. (2) of Ref. 1 that the two-step stability criterion for attachment dominated discharges is given as $\beta \geq (\frac{1+2\delta}{1+\delta})\ \nu_{i_0}$ where $\delta = R_a/(K_d^* + K^+)\ n_{e_0}$.

18. It appears that when the excited states are well mixed by the secondary electron the stability criteria given by Eq. (13) is least restrictive . Before such a conclusion can be reached, other factors, such as the variation of ν_{i_0} and the efficiency of producing the first excited state, have to be considered. These effects will be discussed more fully in a forthcoming report.

DISTRIBUTION LIST

Office of Naval Research, Department of the Navy, Arlington, VA 22217 - Attn: Physics Program (3 copies)

Naval Research Laboratory, Department of the Navy, Washington, D.C. 20375 - Attn: Technical Library (1 copy)

Office of the Director of Defense, Research and Engineering, Information Office Library Branch, The Pentagon, Washington, D.C. 20301 (1 copy)

U.S. Army Research Office, Box CM, Duke Station, Durham, N.C. 27706 (1 copy)

Defense Documentation Center, Cameron Station, Alexandria, VA 22314 (12 copies)

Defender Information Analysis Center, Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201 (1 copy)

Commanding Officer, Office of Naval Research Branch Office, 536 South Clark Street, Chicago, IL 60615 (1 copy)

New York Area Office, Office of Naval Research, 715 Broadway (5th floor), New York, NY 10003 - Attn: Dr. Irving Rowe (1 copy)

San Francisco Area Office, Office of Naval Research, 760 Market Street, Room 447, San Francisco, CA 94012 (1 copy)

Air Force Office of Scientific Research, Department of the Air Force, Washington, DC 22209 (1 copy)

Office of Naval Research Branch Office, 1030 East Green Street, Pasadena, CA 91106 - Attn: Dr. Robert Behringer (1 copy)

Code 102 IP (ONRL), Office of Naval Research, 800 N. Quincy Street, Arlington, VA 22217 (6 copies)

Defense Advanced Research Projects Agency, 1400 Wilson Blvd., Arlington, VA 22209 - Attn: Strategic Technology Office (1 copy)

Office Director of Defense, Research & Engineering, The Pentagon, Washington, DC 20301 - Attn: Ass't. Dir.(Space and Advanced Systems) (1 copy)

Office of the Ass't Secretary of Defense, System Analysis (Strategic Programs), Washington, DC 20301 (1 copy)

U.S. Arms Control and Disarmament Agency, Dept. of State Bldg., Rm. 4931, Washington, DC 20451 - Attn: Dr. Charles Henkin (1 copy)

Energy Research Development Agency, Division of Military Applications, Washington, DC 20545 (1 copy)

National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH 44135 - Attn: Dr. John W. Dunning, Jr (Aerospace Res. Engineer) (1 copy)

National Aeronautics & Space Administration, Code RR, FOB 10B, 600 Independence Ave., SW, Washington, DC 20546 (1 copy)

National Aeronautics and Space Administration, Ames Research Center, Moffett Field, CA 94035 - Attn: Dr. Kenneth W. Billman (1 copy)

Department of the Army, Office of the Chief of RD&A, Washington, DC 20310, Attn: DARD-DD (1 copy)
DAMA-WSM-T (1 copy)

Department of the Army, Office of the Deputy Chief of Staff for Operations & Plans, Washington, DC 20310 - Attn: DAMO-RQD (1 copy)

Ballistic Missile Defense Program Office (BMDPO), The Commonwealth Building, 1300 Wilson Blvd., Arlington, VA 22209 - Attn: Mr. Albert J. Bast, Jr. (1 copy)

U.S. Army Missile Command, Research and Development Division, Redstone Arsenal, ALA 35809 - Attn: Army High Energy Laser Programs (2 copies)

Commander, Rock Island Arsenal, Rock Island, IL 61201 - Attn: SARRI-LR, Mr. J.W. McGarvey (1 copy)

Commanding Officer, U.S. Army Mobility Equipment R&D Center, Ft. Belvoir, VA 22060 - Attn: SMEFB-MW (1 copy)

Commander, U.S. Army Armament Command, Rock Island, IL 61201 - Attn: AMSAR-RDT (1 copy)

Director, Ballistic Missile Defense Advanced Technology Center, P.O. Box 1500, Huntsville, AL 35807 - Attn: ATC-O (1 copy)
ACT-T (1 copy)

Commander, U.S. Army Material Command, Alexandria, VA 22304 - Attn: Mr. Paul Chernoff (AMCRD-T) (1 copy)

Commanding General, U.S. Army Munitions Command, Dover, NH 17801 - Attn: Mr. Gilbert F. Chesnov (AMSMU-R) (1 copy)

Director, U.S. Army Ballistics Res. Lab, Aberdeen Proving Ground, MD 21005 - Attn: Dr. Robert Eichenberger (1 copy)

Commandant, U.S. Army, Air Defense School, Ft. Bliss, TX 79916 - Attn: Air Defense Agency (1 copy)
ATSA-CTD-MS (1 copy)

Commanding General, U.S. Army Combat Dev. Command, Ft. Belvoir, VA 22060 - Attn: Director of Material, Missile Div. (1 copy)

Commander, U.S. Army Training & Doctrine Command, Ft. Monroe, VA 23651 - Attn: ATCD-CF (1 copy)

Commander, U.S. Army Frankford Arsenal, Philadelphia, PA 19137 - Attn: Mr. M. Elnick SARFA-FCD, Bldg. 201-3 (1 copy)

Commander, U.S. Army Electronics Command, Ft. Monmouth, NJ 07703 - Attn: AMSEL-CT-L, Dr. R.G. Buser (1 copy)

Commander, U.S. Army Combine Arms Combat Developments Activity, Ft. Leavenworth, KS 66027 (1 copy)

National Security Agency, Ft. Geo. G. Meade, MD 20755 - Attn: R.C. Foss A763 (1 copy)

Deputy Commandant for Combat & Training Developments, U.S. Army Ordnance Center & School, Aberdeen Proving Ground, MD 21005 - Attn: ATSL-CTD-MSR (1 copy)

Commanding Officer, USACDC CBR Agency, Ft. McClellan, AL 36201 - Attn: CDCCBR-MR (Mr. F.D. Poer) (1 copy)

Department of the Navy, Office of the Chief of Naval Operations, The Pentagon 5C739, Washington, DC 20350 - Attn: (OP 982F3) (1 copy)

Office of Naval Research Branch Office, 495 Summer Street, Boston, MA 02210 - Attn: Dr. Fred Quelle (1 copy)

Department of the Navy, Deputy Chief of Navy Material (Dev.), Washington, DC 20360 - Attn: Mr. R. Gaylord (MAT 032B) (1 copy)

Naval Missile Center, Point Mugu, CA 93042 - Attn: Gary Gibbs (Code 5352) (1 copy)

Naval Research Laboratory, Washington, DC 20375 - Attn: (Code 5503-EOTPO) (1 copy)
Dr. P. Livingston - Code 5560 (1 copy)
Dr. A.I. Schindler - Code 6000 (1 copy)
Dr. H. Shenker - Code 5504 (1 copy)
Mr. D.J. McLaughlin - Code 5560 (1 copy)
Dr. John L. Walsh - Code 5503 (1 copy)

High Energy Laser Project Office, Department of the Navy, Naval Sea Systems Command, Washington, DC 20360 - Attn: CAPT A. Skolnick, USN (PM 22) (1 copy)

Superintendent, Naval Postgraduate School, Monterey, CA 93940 - Attn: Library (Code 2124) (1 copy)

Navy Radiation Technology, Air Force Weapons Lab (NLO), Kirtland AFB, NM 87117 (1 copy)

Naval Surface Weapons Center, White Oak, Silver Spring, MD 20910 - Attn: Dr. Leon H. Schindel (Code 310) (1 copy)
Dr. E. Leroy Harris (Code 313) (1 copy)
Mr. K. Enkenhaus (Code 034) (1 copy)
Mr. J. Wise (Code 047) (1 copy)
Technical Library (1 copy)

U.S. Naval Weapons Center, China Lake, CA 93555 - Attn: Technical Library (1 copy)

HQ USAF (AF/RDPS), The Pentagon, Washington, DC 20330 - Attn: LT COL A.J. Chiota (1 copy)

HQ AFSC/XRLW, Andrews AFB, Washington, DC 20331 - Attn: MAJ J.M. Walton (1 copy)

HQ AFSC (DLCAW), Andrews AFB, Washington, DC 20301 - Attn: MAJ H. Axelrod (1 copy)

Air Force Weapons Laboratory, Kirtland AFB, NM 87117 - Attn: LR (1 copy)
AL (1 copy)

HQ SAMSO (XRTD), P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009 - Attn: LT Dorian DeMaio (XRTD) (1 copy)

AF Avionics Lab (TEO), Wright Patterson AFB, OH 45433 - Attn: Mr. K. Hutchinson (1 copy)

Dept. of the Air Force, Air Force Materials Lab. (AFSC), Wright Patterson AFB, OH 45433 - Attn: MAJ Paul Elder (LPS) (1 copy)
Laser Window Group

HQ Aeronautical Systems Div., Wright Patterson AFB, OH 45433 - Attn: XRF - Mr. Clifford Fawcett (1 copy)

Rome Air Development Command, Griffiss AFB, Rome, NY 13440 - Attn: Mr. R. Urtz (OCSE) (1 copy)

DISTRIBUTION LIST (Continued)

HQ Electronics Systems Div. (ESL), L.G. Hanscom Field, Bedford, MA 01730 - Attn: Mr. Alfred E. Anderson (XRT) (1 copy)
Technical Library (1 copy)

Air Force Rocket Propulsion Lab., Edwards AFB, CA 93523 - Attn: B.R. Bornhorst, (LKCG) (1 copy)

Air Force Aero Propulsion Lab., Wright Patterson AFB, OH 45433 - Attn: COL Walter Moe (CC) (1 copy)

Dept. of the Air Force, Foreign Technology Division, Wright Patterson AFB, OH 45433 - Attn: PDTN (1 copy)

Commendant of the Marine Corps, Scientific Advisor (Code RD-1), Washington, DC 20380 (1 copy)

Aerospace Research Labs., (AP), Wright Patterson AFB, OH 45433 - Attn: LT COL Max Duggins (1 copy)

Defense Intelligence Agency, Washington, DC 20301 - Attn: Mr. Seymour Berler (DTIB) (1 copy)

Central Intelligence Agency, Washington, DC 20505 - Attn: Mr. Julian C. Nall (1 copy)

Analytic Services, Inc., 5613 Leesburg Pike, Falls Church, VA 22041 - Attn: Dr. John Davis (1 copy)

Aerospace Corp., P.O. Box 92957, Los Angeles, CA 90009 - Attn: Dr. G.P. Millburn (1 copy)

Airesearch Manuf. Co., 9851-9951 Sepulveda Blvd., Los Angeles, CA 90009 - Attn: Mr. A. Colin Stancliffe (1 copy)

Atlantic Research Corp., Shirley Highway at Edsall Road, Alexandria, VA 22314 - Attn: Mr. Robert Naismith (1 copy)

Avco Everett Research Lab., 2385 Revere Beach Parkway, Everett, MA 02149 - Attn: Dr. George Sutton (1 copy)
Dr. Jack Daugherty (1 copy)

Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201 - Attn: Mr. Fred Tietzel (STPIAC) (1 copy)

Bell Aerospace Co., Buffalo, NY 14240 - Attn: Dr. Wayne C. Solomon (1 copy)

Boeing Company, P.O. Box 3999, Seattle, WA 98124 - Attn: Mr. M.I. Gamble (2-,460, MS 8C-88) (1 copy)

Electro-Optical Systems, 300 N. Halstead, Pasadena, CA 91107 - Attn: Dr. Andrew Jensen (1 copy)

ESL, Inc., 495 Java Drive, Sunnyvale, CA 94086 - Attn: Arthur Einhorn (1 copy)

General Electric Co., Space Division, P.O. Box 8555, Philadelphia, PA 19101 - Attn: Dr. R.R. Sigismonti (1 copy)

General Electric Co., 100 Plastics Avenue, Pittsfield, MA 01201 - Attn: Mr. D.G. Harrington (Rm 1044) (1 copy)

General Research Corp., P.O. Box 3587, Santa Barbara, CA 93105 - Attn: Dr. R. Holbrook (1 copy)

General Research Corp., 1501 Wilson Blvd., Suite 700, Arlington, VA 22209 - Attn: Dr. Giles F. Crimi (1 copy)

Hercules, Inc., Industrial System Dept., Wilmington, DE 19899 - Attn: Dr. R.S. Voris (1 copy)

Hercules, Inc., P.O. Box 210, Cumberland, MD 21502 - Attn: Dr. Ralph R. Preckel (1 copy)

Hughes Research Labs, 3011 Malibu Canyon Road, Malibu, CA 90265 - Attn: Dr. D. Forster (1 copy)

Hughes Aircraft Co., Aerospace Group - Systems Division, Canoga Park, CA 91304 - Attn: Dr. Jack A. Alcalay (1 copy)

Hughes Aircraft Co., Centinela and Teale Streets, Bldg. 6, MS E-125, Culver City, CA 90230 - Attn: Dr. William Yates (1 copy)

Institute for Defense Analyses, 400 Army-Navy Drive, Arlington, VA 22202 - Attn: Dr. Alvin Schnitzler (1 copy)

Johns Hopkins Uniniversity, Applied Physics Lab, 8621 Georgia Avenue, Silver Spring, MD 20910 - Attn: Dr. Albert M. Stone (1 copy)

Lawrence Livermore Laboratory, P.O. Box 808, Livermore, CA 94550 - Attn: Dr. R.E. Kidder (1 copy)
Dr. E. Teller (1 copy)
Dr. Joe Fleck (1 copy)

Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, NM 87544 - Attn: Dr. Keith Boyer (1 copy)

Lulejian and Associates, Inc., Del Amo Financial Center, 21515 Hawthorne Blvd. - Suite 500, Torrance, CA 90503 (1 copy)

Lockheed Palo Alto Res. Lab., 3251 Hanover St., Palo Alto, CA 94303 - Attn: L.R. Lunsford, Orgn, 52-24, Bldg. 201 (1 copy)

Mathematical Sciences Northwest, Inc., P.O. Box 1887, Bellevue, WN 98009 - Attn: Dr. Abraham Hertzberg (1 copy)

Martin Marietta Corp., P.O. Box 179, Mail Station 0471, Denver, CO 80201 - Attn: Mr. Stewart Chapin (1 copy)

Massachusetts Institute of Technology, Lincoln Laboratory, P.O. Box 73, Lexington, MA 02173 - Attn: Dr. S. Edelberg (1 copy)
Dr. L.C. Marquet (1 copy)

McDonnell Douglas Astronautics Co., 5301 Bolsa Avenue, Huntington Beach, CA 92647 - Attn: Mr. P.L. Klevatt (1 copy)
Dept. A3-830-BBFO, M/S 9

McDonnell Douglas Research Labs, Dept. 220, Box 516, St. Louis, MO 63166 - Attn: Dr. D.P. Ames (1 copy)

MITRE Corp., P.O. Box 208, Bedford, MA 01730 - Attn: Mr. A.C. Cron (1 copy)

North American Rockwell Corp., Autonetics Div., Anaheim, CA 92803 - Attn: Mr. T.T. Kumagi (1 copy)
C/476 Mail Code HA18

Northrop Corp., 3401 West Broadway, Hawthorne, CA 90250 - Attn: Dr. Gerard Hasserjian (1 copy)
Laser Systems Dept.

Physical Sciences, Inc., 18 Lakeside Office Park, Wakefield, Ma 01880 - Attn: Dr. Anthony N. Pirri (1 copy)

RAND Corp., 1700 Main Street, Santa Monica, CA 90406 - Attn: Dr. C.R. Culp/Mr. G.A. Carter (1 copy)

Raytheon Co., 28 Seyon Street, Waltham, MA 02154 - Attn: Dr. F.A. Horrigan (Res. Div.) (1 copy)

Raytheon Co., Boston Post Road, Sudbury, MA 01776 - Attn: Dr. C. Sonnenschien (Equip. Div.) (1 copy)

Raytheon Co., Bedford Labs, Missile Systems Div., Bedford, MA 01730 - Attn: Dr. H.A. Mehlhorn (1 copy)

Riverside Research Institute, 80 West End Street, New York, NY 10023 - Attn: Dr. L.H. O'Neill (1 copy)
Dr. John Bose (1 copy)
(HPEGL Library) (1 copy)

R&D Associates, Inc., P.O. Box 3580, Santa Monica, CA 90431 - Attn: Dr. R.E. LeLevier (1 copy)

Rockwell International Corporation, Rocketdyne Division, Albuquerque District Office, 3636 Menaul Blvd., NE, Suite 211, Albuquerque, NM 87110
Attn: C.K. Kraus, Mgr. (1 copy)

SANDIA Corp., P.O. Box 5800, Albuquerque, NM 87115 - Attn: Dr. Al Narath (1 copy)

Stanford Research Institute, Menlo Park, CA 94025 - Attn: Dr. F.T. Smith (1 copy)

Science Applications, Inc., 1911 N. Ft. Meyer Drive, Arlington, VA 22209 - Attn: L. Peckam (1 copy)

Science Application, Inc., P.O. Box 328, Ann Arbor, MI 48103 - Attn: R.E. Meredith (1 copy)

Science Applications, Inc., 6 Preston Court, Bedford, MA 01703 - Attn: R. Greenberg (1 copy)

Science Applications, Inc., P.O. Box 2351, La Jolla, CA 92037 - Attn: Dr. John Asmus (1 copy)

Systems, Science and Software, P.O. Box 1620, La Jolla, CA 92037 - Attn: Alan F. Klein (1 copy)

Systems, Consultants, Inc., 1050 31st Street, NW, Washington, DC 20007 - Attn: Dr. R.B. Keller (1 copy)

Thiokol Chemical Corp., WASATCH Division, P.O. Box 524, Brigham City, UT 84302 - Attn: Mr. J.E. Hansen (1 copy)

TRW Systems Group, One Space Park, Bldg. R-1, Rm. 1050, Redondo Beach, CA 90278 - Attn: Norman Campbell (1 copy)

United Technologies Research Center, 400 Main Street, East Hartford, CT 06108 - Attn: Mr. G.H. McLafferty (3 copies)

United Technologies Research Center, Pratt and Whitney Acft. Div., Florida R&D Center, West Palm Beach, FL 33402 - Attn: Dr. R.A. Schmidtke (1 copy)
Mr. Ed Pinsley (1 copy)

VARIAN Associates, EIMAC Division, 301 Industrial Way, San Carlos, CA 94070 - Attn: Mr. Jack Quinn (1 copy)

DISTRIBUTION LIST (Continued)

Vought Systems Division, LTV Aerospace Corp., P.O. Box 5907, Dallas, TX 75222 - Attn: Mr. F.G. Simpson, MS 254142 (1 copy)
Westinghouse Electric Corp., Defense and Space Center, Balt-Wash. International Airport - Box 746, Baltimore, MD 21203 - Attn: Mr. W.F. List (1 copy)
Westinghouse Research Labs, Beulah Roak, Churchill Boro, Pittsburgh, PA 15235 - Attn: Dr. E.P. Riedel (1 copy)
United Technologies Research Center, East Hartford, CT 06108 - Attn: A.J. deMaria (1 copy)
Airborne Instruments Laboratory, Walt Whitorian Road, Melville, NY 11746 - Attn: F. Pace (1 copy)
General Electric R&D Center, Schenectady, NY 12305 - Attn: Dr. Donald White (1 copy)
Cleveland State University, Cleveland, OH 44115 - Attn: Dean Jack Soules (1 copy)
EXXON Research and Engineering Co., P.O. Box 8, Linden, NJ 07036 - Attn: D. Grafstein (1 copy)
University of Maryland, Department of Physics and Astronomy, College Park, MD 20742 - Attn: D. Currie (1 copy)
Sylvania Electric Products, Inc., 100 Fergeson Drive, Mountain View, CA 94040 - Attn: L.M. Osterink (1 copy)
North American Rockwell Corp., Autonetics Division, 3370 Miraloma Avenue, Anaheim, CA 92803 - Attn: R. Gudmundsen (1 copy)
Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02138 - Attn: Prof. A. Javan (1 copy)
Lockheed Missile & Space Co., Palo Alto Research Laboratories, Palo Alto, CA 94304 - Attn: Dr. R.C. Ohlman (1 copy)
ILC Laboratories, Inc., 164 Commercial Street, Sunnyvale, CA 94086 - Attn: L. Noble (1 copy)
University of Texas at Dallas, P.O. Box 30365, Dallas, TX 75230 - Attn: Prof. Carl B. Collins (1 copy)
Polytechnic Institute of New York, Rt. 110, Farmingdale, NY 11735 - Attn: Dr. William T. Walter (1 copy)